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Numerical Simulation of Flow Field in a Rectangular Micro-channel

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Abstract. The behavior of the flow field in a rectangular micro-channel was numerically investigated using shear stress transport model. The γ-Reθt transition model, laminar model and shear stress transport model are used to comparing the flow transition in the micro-channel. Results indicate that the laminar model and the γ-Reθt transition model produce similar pressure drops when the mass flow rate is smaller. When the mass flow rate increases, values predicted by the γ-Reθt transition model matches best with the experimental data. The laminar model and the SST model are incapable of predicting transition, while the γ-Reθt transition model forecasts the critical Reynolds number well and the predicted values match well with the experimental data. In the present study, the transition is accurately simulated and the flow mechanism is revealed. For microchannels with $L/D \geq 100$, the transition from laminar to turbulent regime occurs for a Reynolds number in the range 2000-2500, and the length-to-diameter ratio has no significant effect on the critical Reynolds number.

Keywords: flow field, micro-channel, numerical simulation, turbulent model

1 Introduction

In modern gas turbine blades, internal forced convection is one of the most classical and popular methods used for keeping an adequate temperature of the blade material. As one of the effective types for the internal forced convection, serpentine passage in the middle section of turbine blade has been investigated, improved, and applied in the turbine blades for more than thirty years, which has been reviewed by Han and Huh [1].

Mala and Li [2] conducted experiments to investigate the behavior of water flow in microtubes of stainless steel and fused silica with diameters ranging from 50 to 254 μm. The results indicated the friction factor at higher Reynolds number was bigger than that predicted by the conventional theory. The flow characteristics also exhibited material dependence. Moreover, the authors attributed the earlier transition to the effects of surface roughness. Zhang et al. [3] measured the pressure drop in six multiport microchannel flat tubes with different geometry parameters and calculated the friction factor. In the experiments, an earlier transition was observed and the aspect ratio seems to correlate with that. Additionally, the entrance effect seemed to have a significant impact on the friction factor especially at higher Reynolds numbers. Toh et al. [4] developed a numerical procedure based on the finite volume method (FVM) to study the flow behavior of water flows in the laminar regime in heated microchannels. The method was validated by comparing the numerical results with the experimental data of Tuckerman [5]. Mokrani et al. [6] reported the conclusion from their experiments that for microchannels of channel heights between 50 and 500 μm, the conventional laws and correlations describing the flow in large-scale

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channels remained applicable. Moreover, no earlier transition was observed in the tests. Sahar et al. [7] performed a numerical study with FLUENT to investigate the flow behavior of water and R134a in a single rectangular microchannel with different geometric models. The 2D model predicted a lower value for the friction factor while the 3D thin-wall model exhibited a transition change at Re≈1600, corresponding with the experimental data. Zhang et al. [8] measured the pressure drop in six multiport microchannel flat tubes with different geometry parameters and calculated the friction factor. In the experiments, an earlier transition was observed and the aspect ratio seems to correlate with that. Additionally, the entrance effect seemed to have a significant impact on the friction factor especially at higher Reynolds numbers. Hu et al. [9] developed a finite-volume-based numerical model to investigate the velocity distribution and the pressure drop in microchannels. The simulation results revealed that the height, size and spacing of the roughness elements all made a difference. Rawool et al. [10] numerically investigated the relationship between the friction factor and the roughness height, geometry and Reynolds number. It was observed that the friction factor of the rectangular and triangular obstructions is higher than the trapezoidal ones. The friction factor decreases with the increase of Reynolds number in a nonlinear trend and increase nonlinearly with the increase of the roughness height.

Over these years, the research on fluid flow in microchannels mainly focused either on the characteristics of the flows (such as the pressure drop through the microchannels, friction factor and the critical Reynolds number, etc.), or on the factors which have an impact on the behavior of the flows (such as compressibility, roughness, velocity slip and temperature jump, etc.). But unfortunately, most of the investigations only described the overall and average behavior of microfluidics because the test technique is not enough to capture the details of flows in microfluidics. Moreover, the study on the flow mechanism in a single microchannel is not sufficient. In the case of numerical study, most investigators would use a laminar model for laminar flows or turbulence models without considering the transition in the channels. The present study attempts to introduce the transition model into the numerical simulation and to verify the validity of the model by comparing the predicted values with the experimental data. The entrance effect has an obvious influence on the flow characteristics in short microchannels as observed in short microchannels, however, it is unclear to what extent the entrance region affects the flow behavior in microchannels with different lengths, so the effect of length-to-diameter ratio on the critical Reynolds number is also investigated.

2 Numerical Method and Validation

2.1 Numerical Method

According to the experimental results, the critical Reynolds number is about 2100. To simulate transition, in addition to direct numerical simulation (DNS) and large eddy simulation (LES), transition models have been developing rapidly during the past years. Generally, four models are adopted in engineering application, namely, low Reynolds number models, models based on turbulence intermittency, laminar kinetic energy transition models and instability wave models.

The CFD software ANSYSCFX 15.0 was used to numerically simulate the flow through the microchannel. In the simulation, ideal air at 299.15K was selected as the working fluid. Boundary conditions for the six boundaries were specified for this simplified computational domain. At the entrance, the inlet mass flow rate and the air temperature were employed. The outlet boundary condition was set as pressure outlet. Symmetry was assigned for the two symmetrical planes. No-slip boundary condition was imposed on the other two boundaries which were also assumed to be adiabatic and smooth.

2.2 Physical Model and Computational Domain

The experiments involved in this simulation were carried out in a self-designed test rig as illustrated in Zhu et al. [8] with a detailed depiction of the experiment setup and methods. There were 22 microchannels in the test piece and all channels were assumed to be the same. The length of every microchannel was 90 mm and the size of the cross section was 0.4 mm×0.4 mm, presented in Fig. 1.

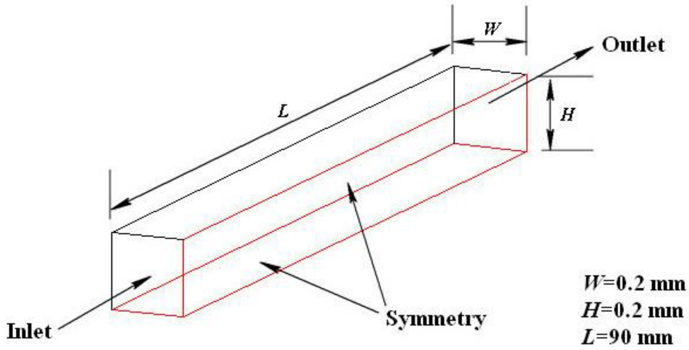


Fig. 1. Computational domain used for the simulation

2.3 Grid Independence Analysis

The gridding was carried out in ICEM. The geometric construction of the selected computational domain was straightforward, so structured hexahedral elements were adopted for high-quality grids. In order to achieve a balance between the solution accuracy and the computation time, grid independence was verified respectively for the three flow models. Taking the DM model as an example, the case at Re=2000 is shown in Table1, where Nis the number of cells. Variables with subscript I and i-1meanthe values of parameters for the current grid and the last grid, respectively. With the criterion $\left|\left(\Delta p_i - \Delta p_{i-1}\right)/\Delta p_{i-1}\right| < 1\%$, grid 4 was chosen for the present simulation.

Table 1. Grid independence analysis with model at *Re*=2000

Case	*N*	*Ni/Ni-1*	*Δp(Pa)*	$\left|\left(\Delta p_i - \Delta p_{i-1}\right)/\Delta p_{i-1}\right|$ (%)
Grid 1	168480	--	31994.8	--
Grid 2	306965	1.82	31164	2.60
Grid 3	605085	1.97	30117.8	3.36
Grid 4	1041005	1.72	29242.7	2.91
Grid 5	1861745	1.79	29330.9	0.30
Grid 6	3026685	1.63	29242.9	0.30

3 Results and Discussion

3.1 Pressure Drop and Friction Factor

The pressure drops measured in the experiments and predicted by the simulation are illustrated in Fig. 2.

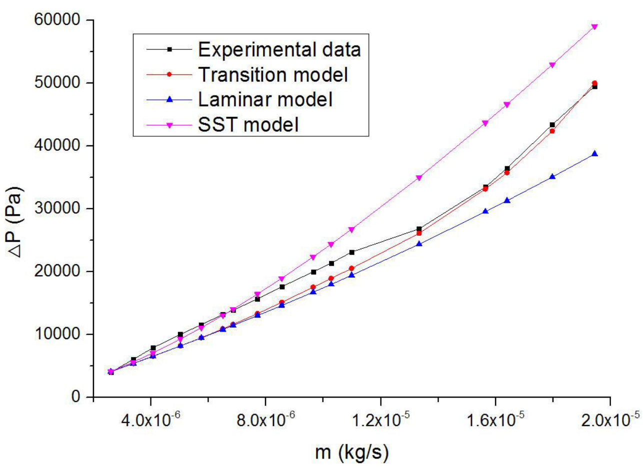


Fig. 2. Pressure drop of different models with mass flow rate

As shown in Fig. 2, the pressure drops predicted by the SST model are always higher than the pressure drop predicted by the other models. The laminar model and the γ-Reθt transition model predict similar pressure drops when the mass flow rate is smaller. The values predicted by the laminar model and SST model depart further from the experimental data with the increase of the mass flow rate.

The variations of the friction factor predicted by the various models as a function of Reynolds are plotted on a logarithmic scale in Fig. 3.

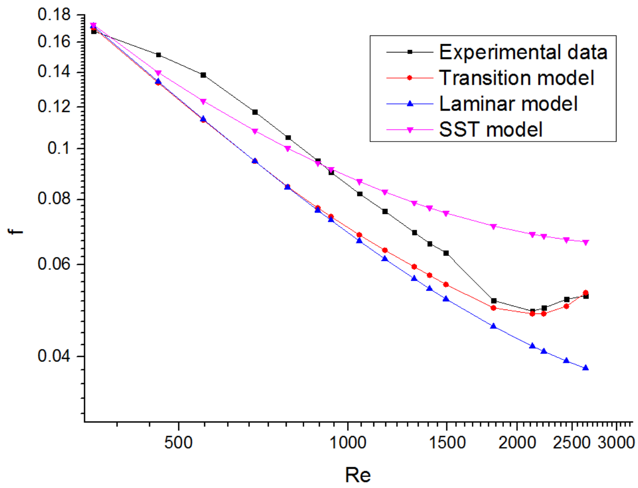


Fig. 3. Friction factor of different models with Reynolds number

According to the experimental results, the critical Reynolds number of the flow transition was around 2100. As shown in Fig. 3, neither the laminar model nor the SST model predicts the correct trend of transition. The γ-Reθt transition model captures the range where the critical Reynolds number lies, nonetheless the predicted values deviates from the experimental ones.

The main reason for the errors in pressure drop and friction factor is considered to be that the numerical simulation computed the pressure drop along the microchannel while in the actual experiments there were pressure losses at the inlet and the outlet. That would make the calculated pressure drops under predict the true values.

3.2 Turbulent Intermittency

Fig. 4 depicts the distribution contours of turbulent intermittency on the symmetry plane at different Reynolds numbers. In the figure, left of the microchannel is the inlet and right is the outlet.

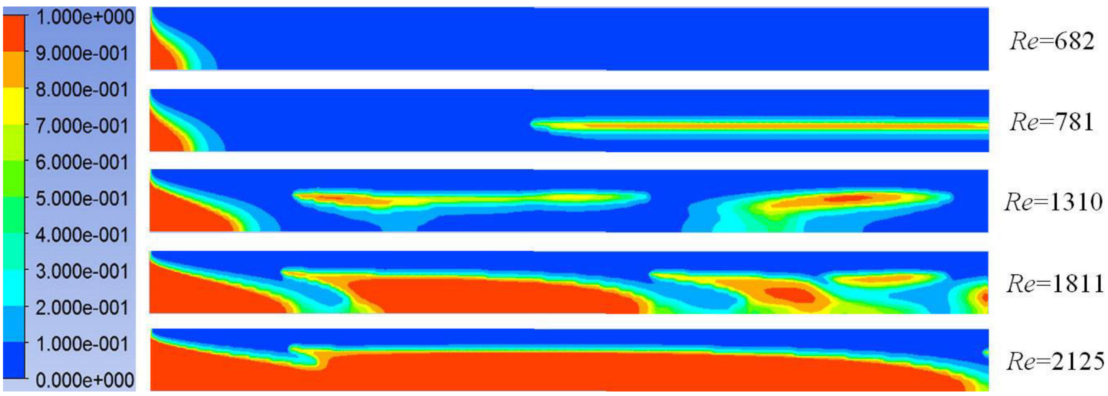


Fig. 4. Contours of turbulent intermittency

As shown in Fig. 4, for a small Reynolds number, the turbulent region only exists at the entrance of the microchannel due to the inlet turbulence. It is interesting to observe that local turbulent regions appear at the rear of the channel before the Reynolds number reaches the critical value. With the Reynolds number increasing, the influence of the incoming flow grows greater. Meanwhile, local turbulent regions appear at the rear of the channel. And with the Reynolds number increasing, the stream wise position where the local turbulent regions begin to appear gets closer to the inlet and the regions expand as well. When the Reynolds number is more than 2125, the inlet turbulent region connects with the downstream regions in the microchannel.

According to Fig. 4, there are no turbulent regions at the rear of the channel when the Reynolds number is less than 682. This is the reason for the similar simulation results.

3.3 Effect of Length-to-diameter Ratio on Transition

With the DM model chosen, the effect of length-to-diameter ratio on the critical Reynolds number was studied in this section. In the simulation, the cross-sectional size (0.4mm×0.4mm) of the channels was unchanged, as a result, the hydraulic diameter D remained constant. The length of channels was changed so the length-to-diameter ratio (L/D) varied.

The flow behavior with L=10, 30, 40, 50,70, 90, 110, 200 mm under different Reynolds numbers were simulated and the results are shown in Fig. 5. From Fig. 5, it can be observed that for L/D≥100, the transition from laminar to turbulent regime occurs for a Reynolds number in the range 2000-2500, which is consistent with the traditional theory. In the case of L/D=25or 75(corresponding to length 10 mm and 30mm), the flow behavior is so strongly influenced by the entrance region that the friction factor shows no abrupt change. The critical L/D value seems to lie between 75 and 100, so L/D≥100is suggested to eliminate the influence of the entrance effect in the investigation of microchannel flow.

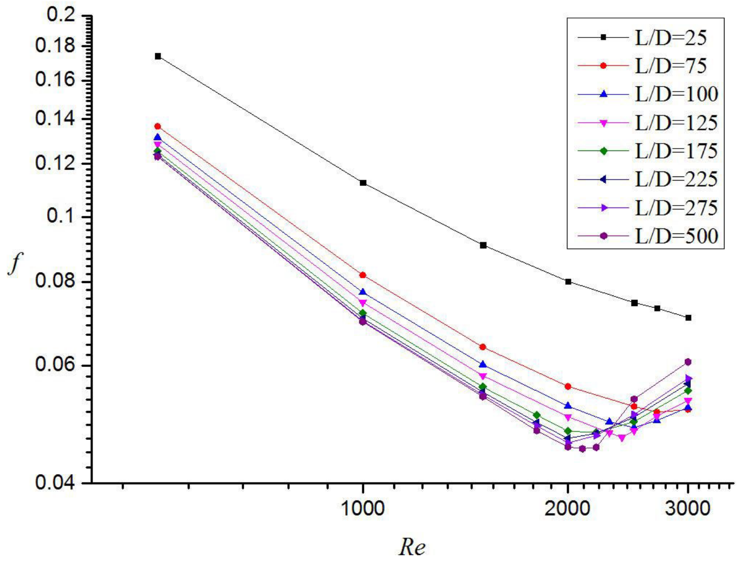
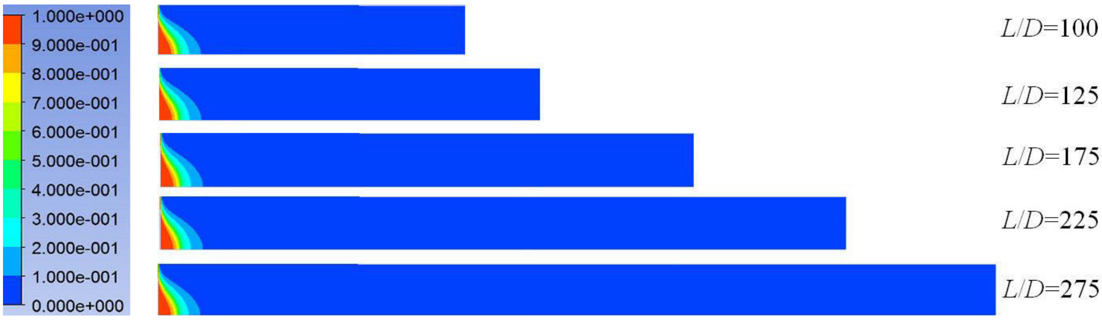
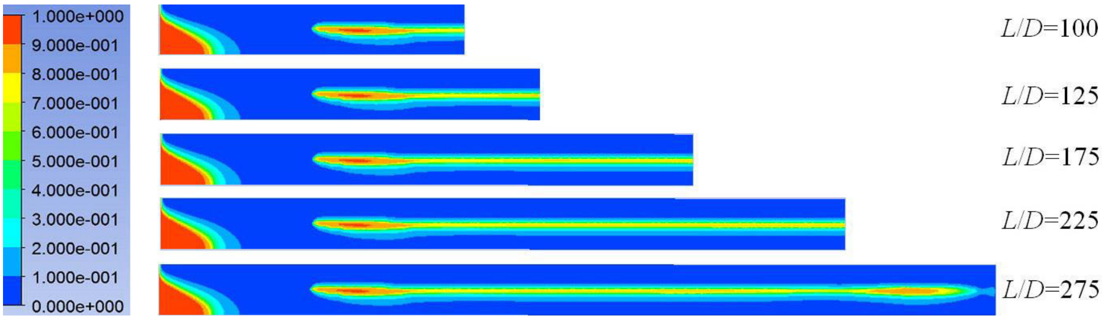


Fig. 5. Effect of length-to diameter ratio on the critical Reynolds number

Fig. 6 presents the distribution of turbulent intermittency for different length-to-diameter ratios at Re=500 and 1000.For Re=500, no local turbulent region is observed. For Re=1000, the local turbulent regions appear at almost the same stream wise position for different length-to-diameter ratios.



(a) Re=500



(b) Re=1000

Fig. 6. Contours of turbulent intermittency for different length-to-diameter ratios

4 Conclusions

Numerical simulation of gas flow in a rectangular microchannel was conducted with the γ-Reθt transition model, the laminar model and the SST model. The conclusions are as follows:

(1) In terms of pressure drop, the laminar model and the γ-Reθt transition model predict similar results when the mass flow rate is small. When the mass flow rate gets higher, values predicted with the γ-Reθt transition model matches best with the experimental data.

(2) Among the three flow models, only the γ-Reθt transition model captures the range where the critical Reynolds number lies despite deviations from the experimental data.

(3) According to the contours of turbulence intermittency, before the Reynolds number reaches the critical value, local turbulent regions appear at the rear of the microchannel and the regions expand with increasing Reynolds number.

(4) The transition from laminar to turbulent regime occurs for Reynolds number in the range 2000-2500 for channels with L/D≥100. In the investigation of flow in microchannels, L/D≥100 is suggested to eliminate the influence of the entrance effect.

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